Performance of CW Superconducting Cavity at ERL test Facility

Feng QIU (KEK)

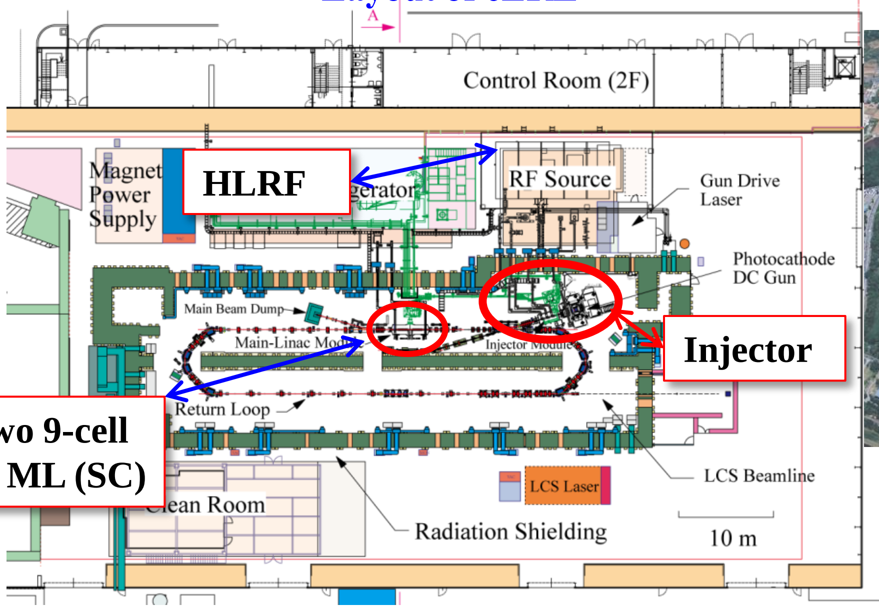
Main Content

- Introduction
- High Power Level RF system
- Low Level RF system
- Gain Scanning
- Performance
- Future Plan
- Summary

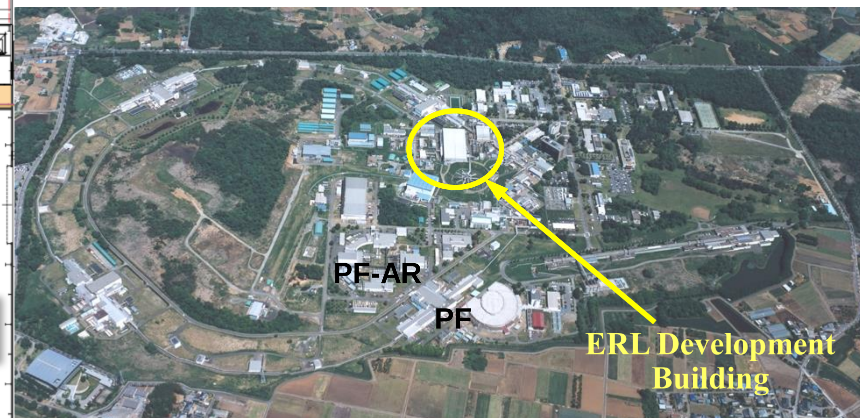
Introduction

■ Compact ERL (cERL) is under construction as a test facility for the future 3-GeV ERL project. It is a superconducting system and is operated in CW mode.

Layout of cERL



Construction Site@KEK



Commissioning of injector started in April, 2013.

Injector consists of 4 cavities: Buncher (NC), Injector 1 (SC), Injector 2 (SC), Injector 3 (SC). ML includes two 9-cell cavities (SC).

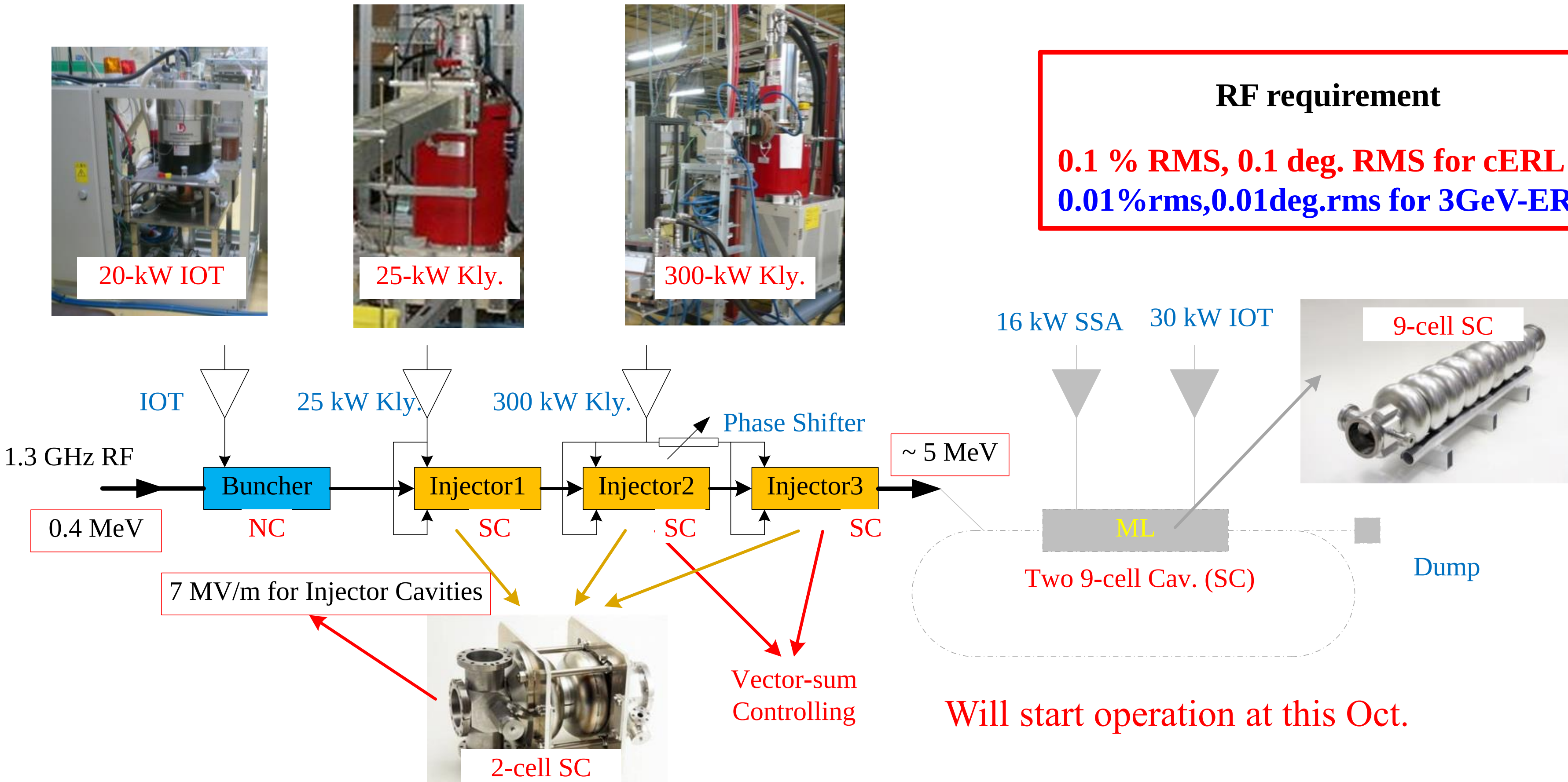
■ At present, the injector was constructed and the first beam commissioning was performed from April to June of this year at cERL. The construction of the Main linac would be carried out by October, 2013.

HLRF (Power Source)

- At present, total 3 kinds of Power Sources are applied in cERL : 20-KW IOT, 25-KW Klystron and 300 KW Klystron.
- The 1.3 GHz 2-cell cavities are used as superconductive cavities.

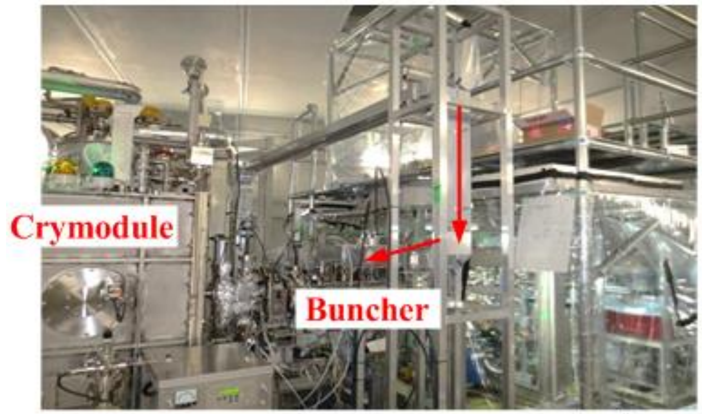
RF requirement

0.1 % RMS, 0.1 deg. RMS for cERL
0.01%rms,0.01deg.rms for 3GeV-ERL

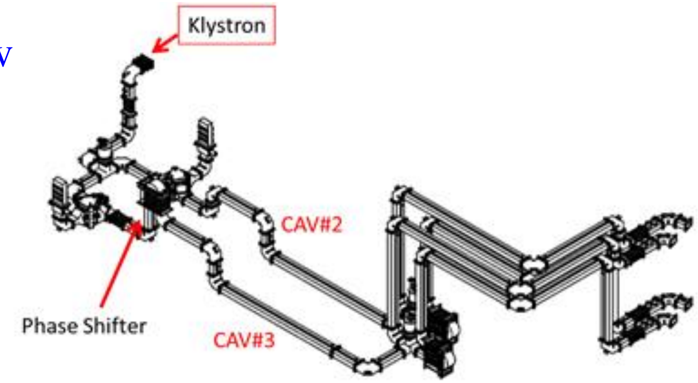


Will start operation at this Oct.

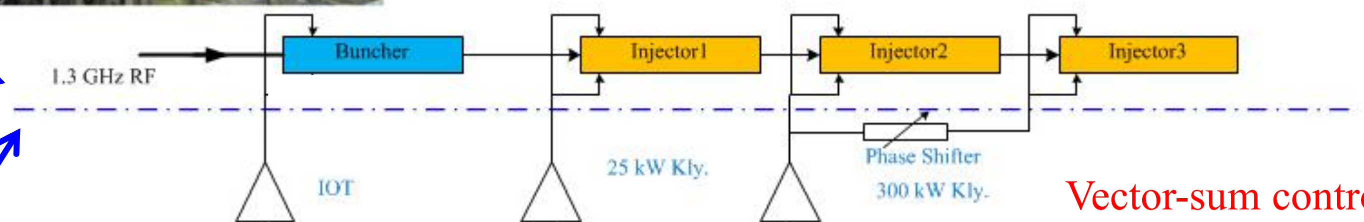
HLRF (Power Distribution System)



Rather narrow space and complicated waveguide.

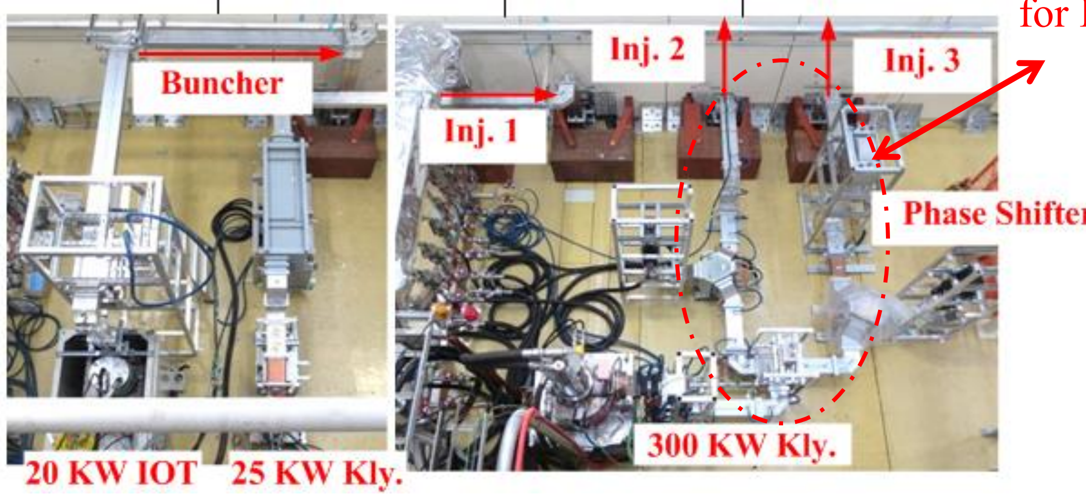


Inside shield

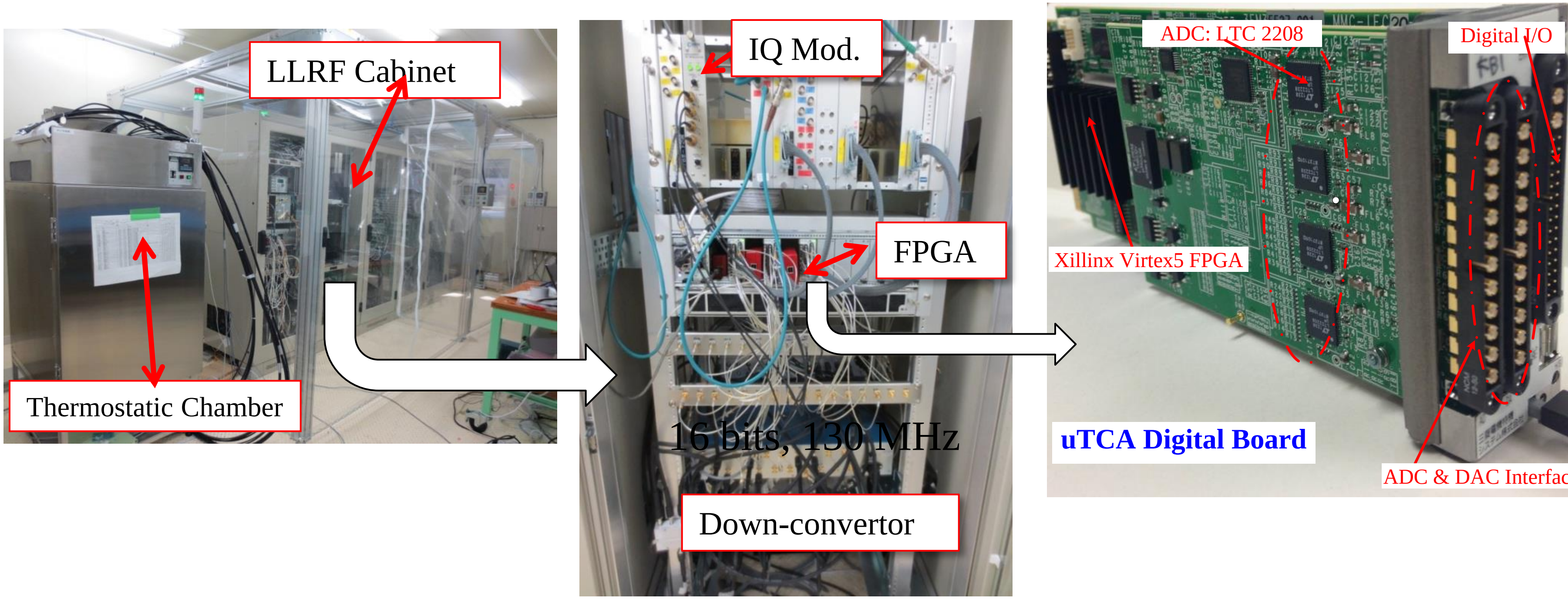


Outside shield

Vector-sum controlling for Inj.2 and Inj. 3.



Low Level RF System

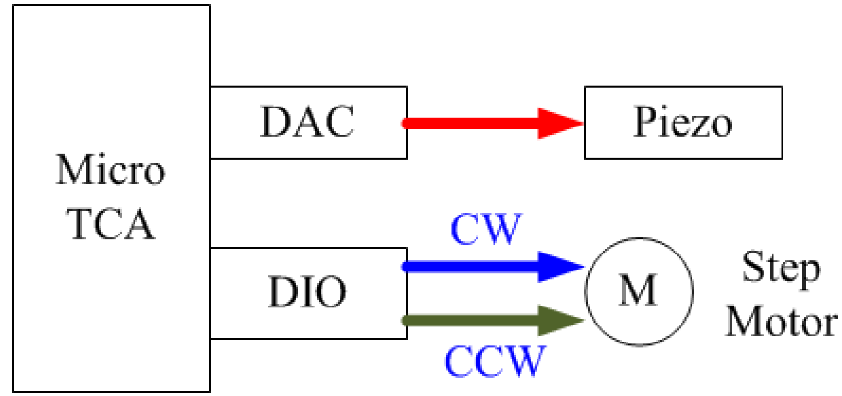


Digital Board	type	Feature
ADC	LTC2208	16 bits, 130 MHz (Max.)
DAC	AD9783	16 bits, 500 MHz (Max.)
FPGA	Virtex 5 FX	550 MHz (Max.), includes a Power PC with Linux, EPICS is installed on the Linux.

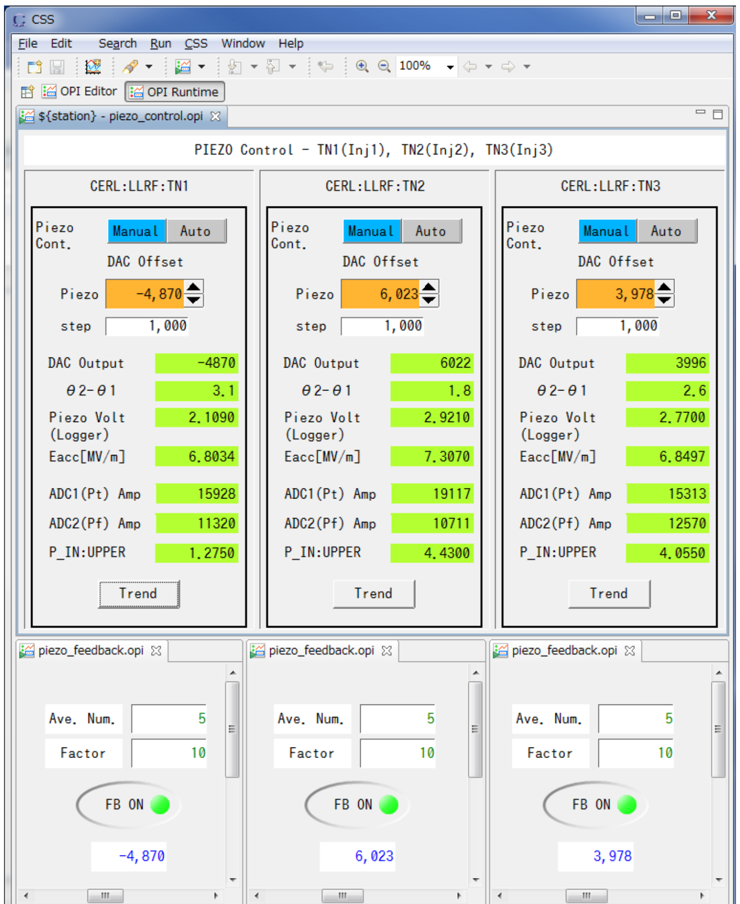
LLRF (2013), F. QIU

Low Level RF System

- We use Piezo+Motor for the tuner controlling .



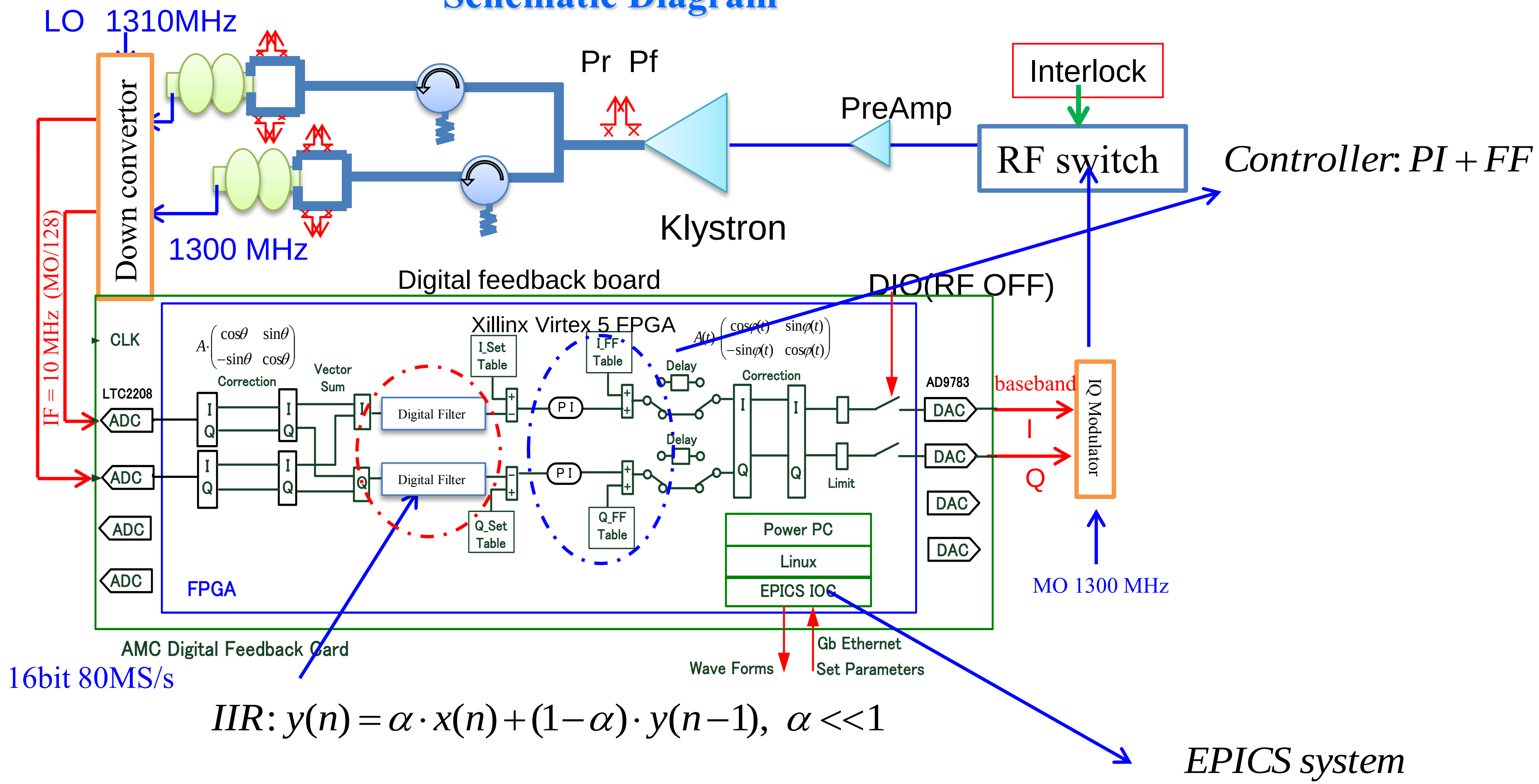
CSS Interface (user interface)



- EPCIS (Experimental Physics and Industrial Control System) is installed inside Micro TCA and is used as the DAQ (data acquisition) system.
- CSS (Control System Studio) is in charge of the user interface programming.

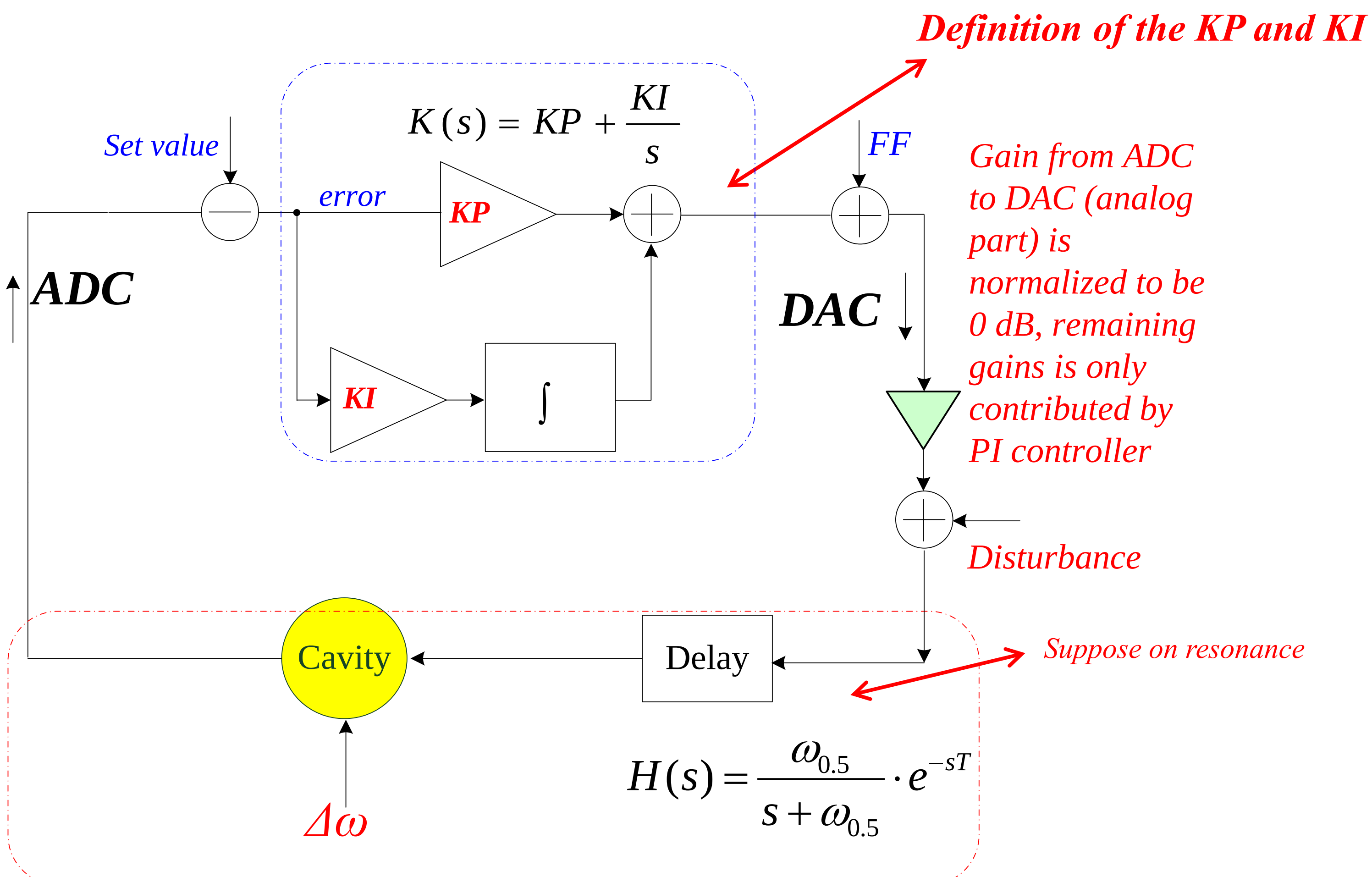
Low Level RF System

Schematic Diagram



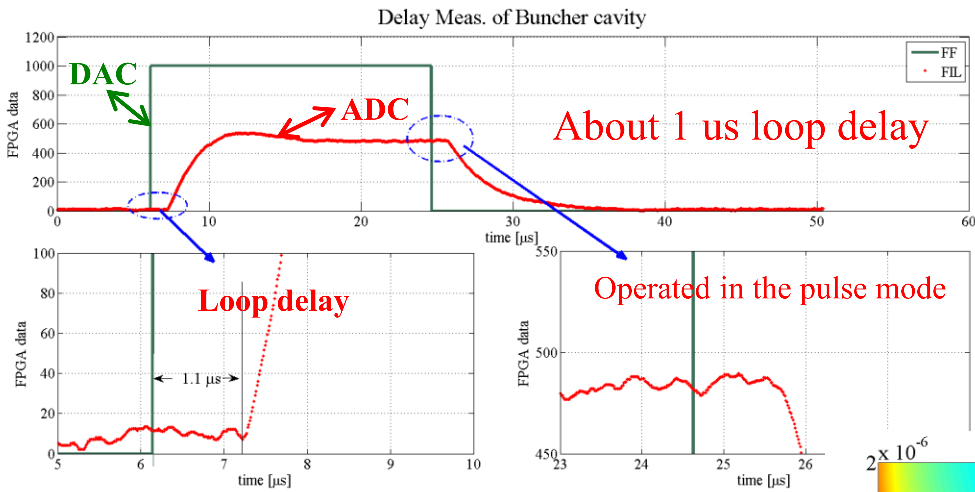
Gain scanning (Definition of Gain)

- Gain-scanning: Scanning different proportional gain KP and integral Gain KI to find out the optimal gains.
- The scanning experiment was carried out at low RF field.

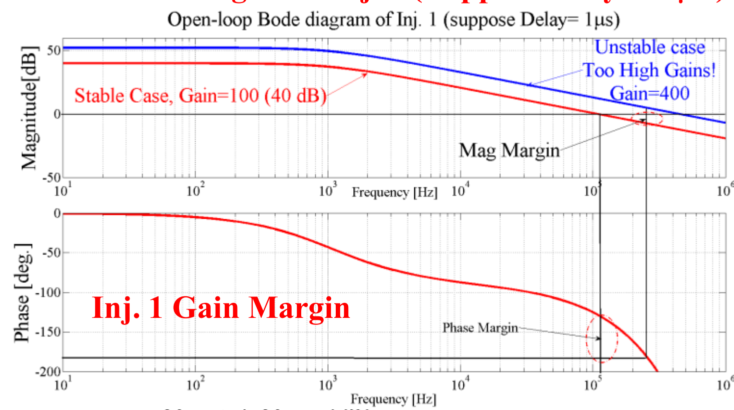


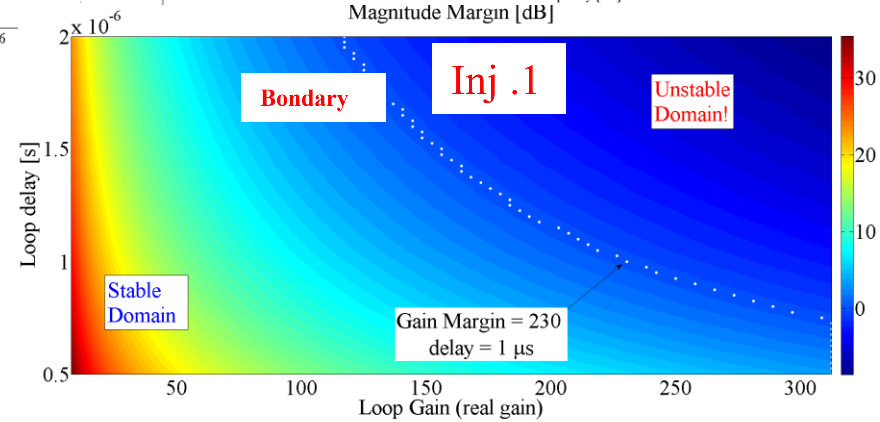
Gain Scanning (Delay measurement)

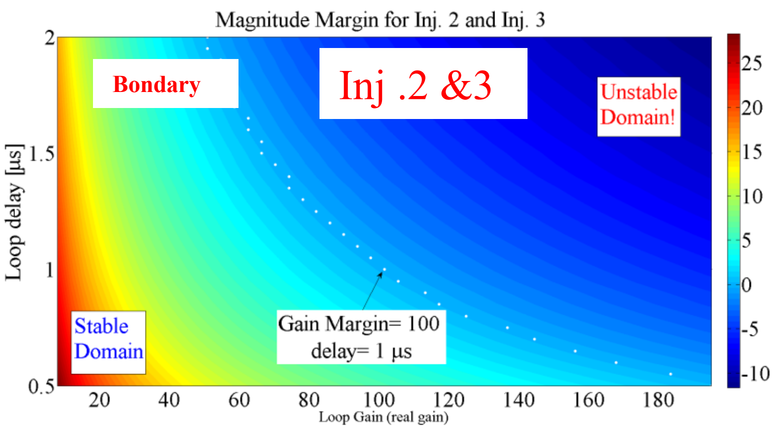
- In order to acquire some priori information about the maximum gain, we have evaluated the loop delay at first due to there is a relationship between the loop delay and the maximum gains.
- Loop delay is measured by exciting the system with square wave in the DAC output.



Gain margin for Inj .1 (suppose delay = 1 μs)





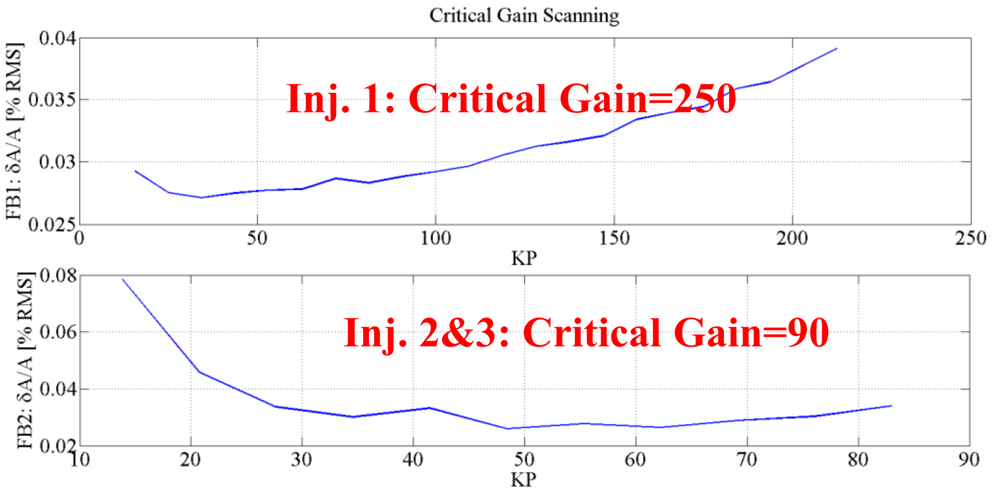


Simulation Gain margin: Inj1=230, Inj. 2&3=100

Gain scanning (Critical gains)

- The Critical gain has measured by the KI=0, KP Scanning.
- If the proportional gain is larger than the critical gain, the loop would be oscillated.

Stb	Bun.	Inj. 1	Inj. 2	Inj. 3
QL	1.1e4	1.2e6	5.8e5	4.8e5
$f_{0.5}$ [kHz]	58	**0.54**	**1.12**	**1.35**



Gain	Inj. 1	Inj. 2&3
Gain Margin (Sim.)	230	100
Critical Gain (Meas.)	Meas. **250**	**90**

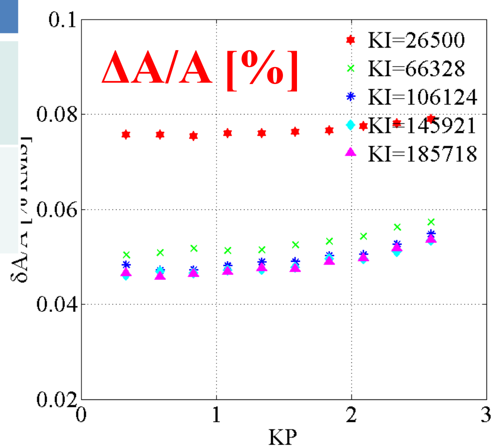
The simulation and the measurement are in agreement very well.

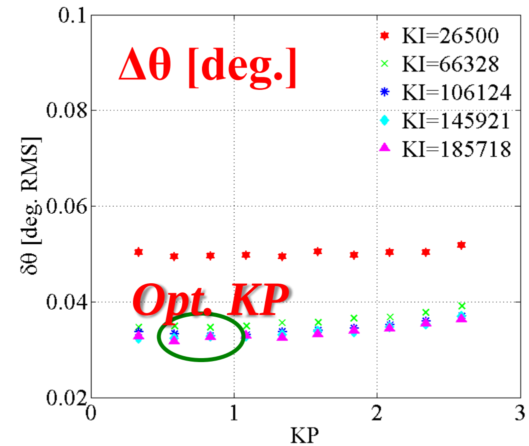
Gain scanning (Buncher)

- High gain is not available for Buncher cavity (NC) due to its large bandwidth (QL=1.1e4) .

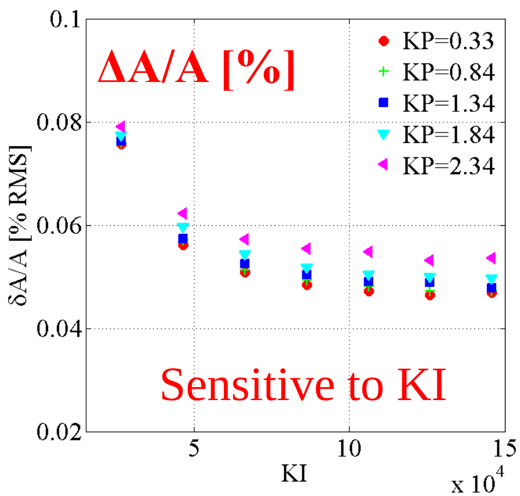
Stb	Bun.	Inj. 1	Inj. 2	Inj. 3
QL	**1.1e4**	1.2e6	5.8e5	4.8e5
$f_{0.5}$ [kHz]	**58**	0.54	1.12	1.35

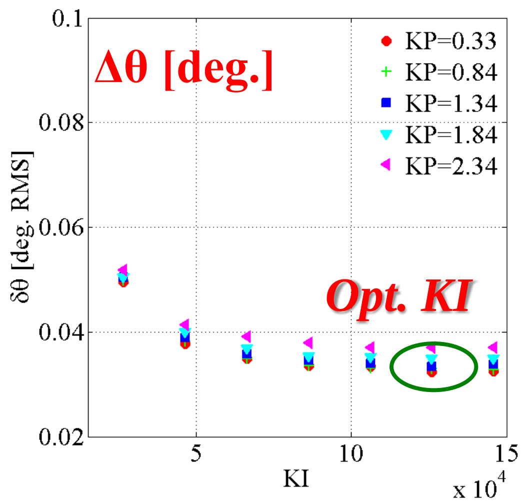
KI=const. KP scanning





KP=const. KI scanning





Optimal Gains:
KP_{opt}=0.8, KI_{opt}=1.2e5.

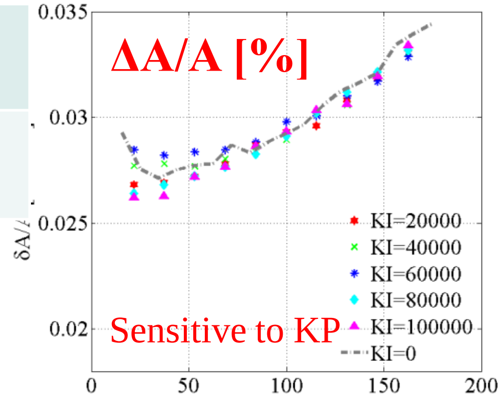
- It is clear to see that the integral Gain KI is dominant gain for the Buncher cavity because of the limitation of high proportional gain KP (not available).

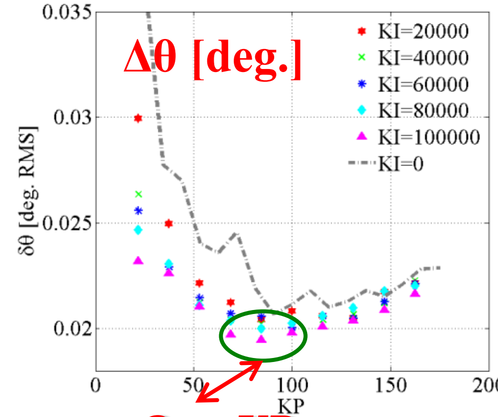
Gain scanning (Inj. 1)

- High gain is available for Inj .1 cavities (SC).

Stb	Bun.	Inj. 1	Inj. 2	Inj. 3
QL	1.1e4	**1.2e6**	5.8e5	4.8e5
$f_{0.5}$ [kHz]	58	**0.54**	1.12	1.35

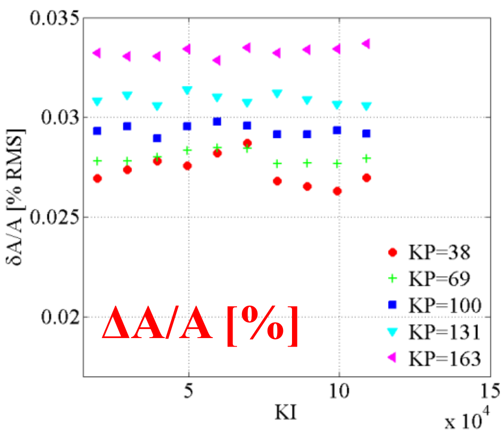
KI=const. KP scanning

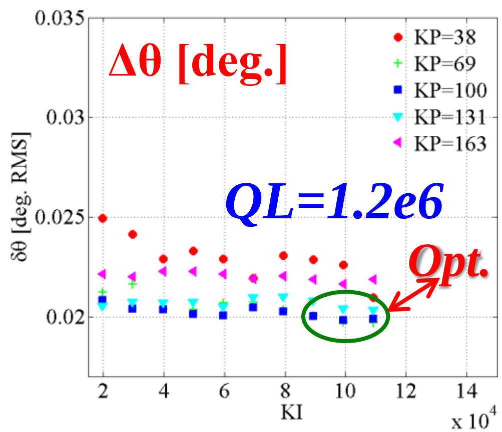




Opt. KP

KP= const., KI scanning





QL=1.2e6

Opt. KI

Optimal Gains:
KP_{opt}=84, *KI_{opt}*=1.0e5.

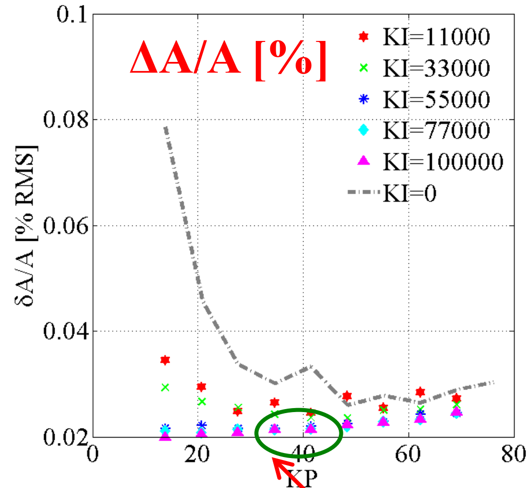
- The dominant gain in Inj. 1 is proportional gain (KP), very common in SC cavity controlling.
- High gain controlling can be realized due to its narrow bandwidth.

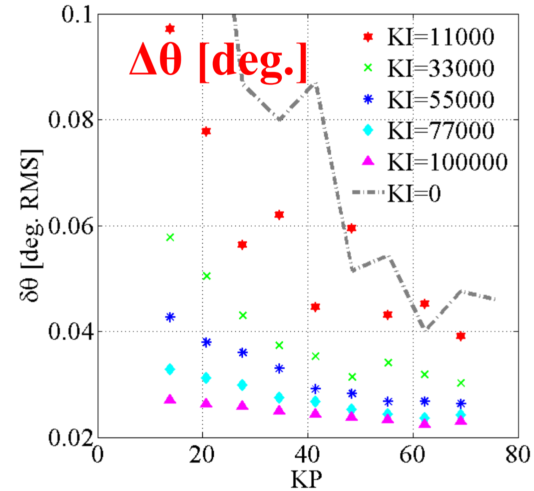
Gain scanning (Inj. 2&3)

- High gain is available for Inj .2 (SC) and Inj .3 (SC).

Stb	Bun.	Inj. 1	Inj. 2	Inj. 3
QL	1.1e4	1.2e6	**5.8e5**	**4.8e5**
f0.5 [kHz]	58	0.54	**1.12**	**1.35**

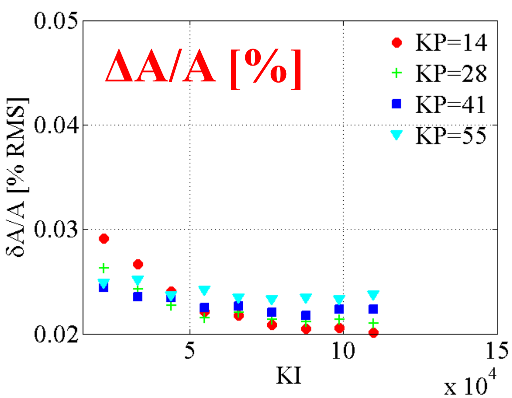
KI=const., KP scanning

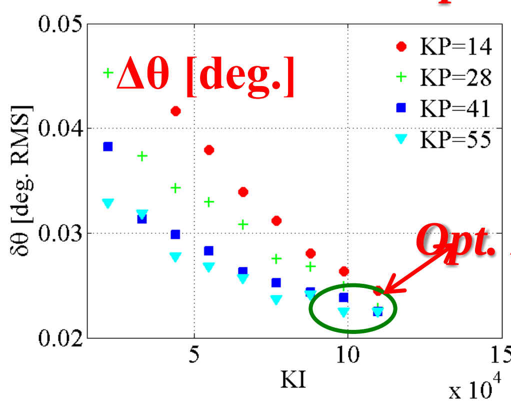




Opt. KP

KP= const., KI scanning





Opt. KI

Optimal Gains:
*KP*opt=41, *KI*opt=1.1e5.

- Both KI and KP have an effect for Inj. 2&3.
- KI is also significant due to there is an 300 Hz component in the HVPS.

Gain scanning (Conclusion)

Conclusions:

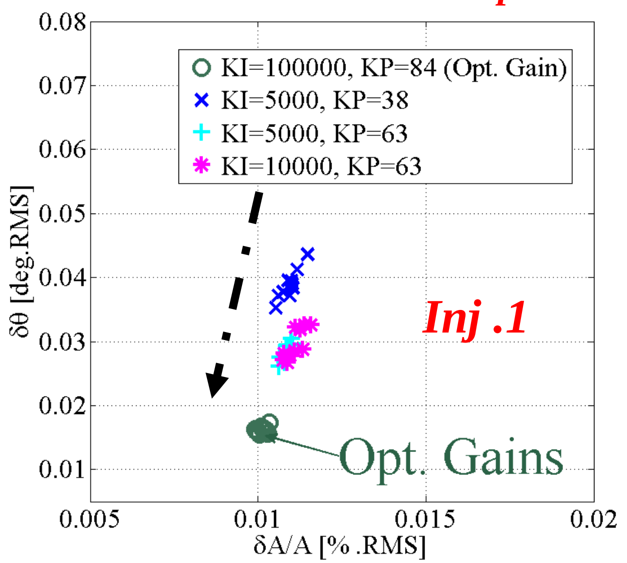
- The proportional gain KP plays an much more important roles in SC cavity and it is usually located in the ½ to ⅓ of the critical gains.
- The integral gain KI is significant in NC cavity due to the limitation of the critical gains.

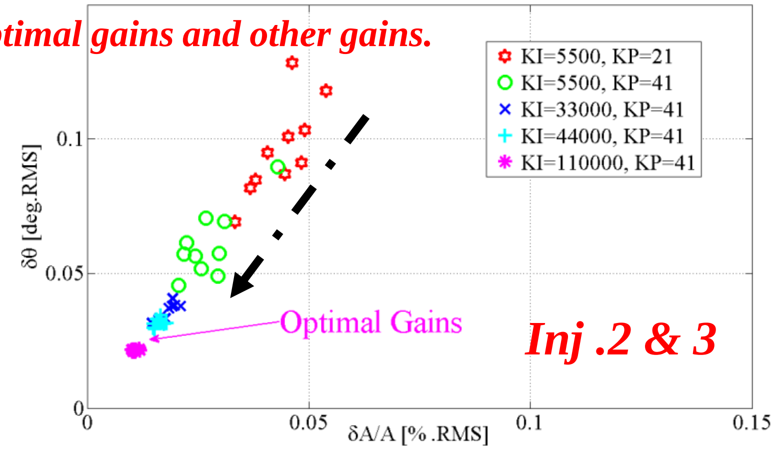
Vector-sum

Gain	Bun.	Inj. 1	Inj. 2	Inj .3
Prop. Gain (KP)	0.8	84	41	
Int. Gain (KI)	1.2e5	1.0e5	1.1e5	
Critical Gain	3	230	90	
$f_{0.5}$ [kHz]	58	0.54	1.12	1.35

About ½ to ⅓

Comparison btw the optimal gains and other gains.





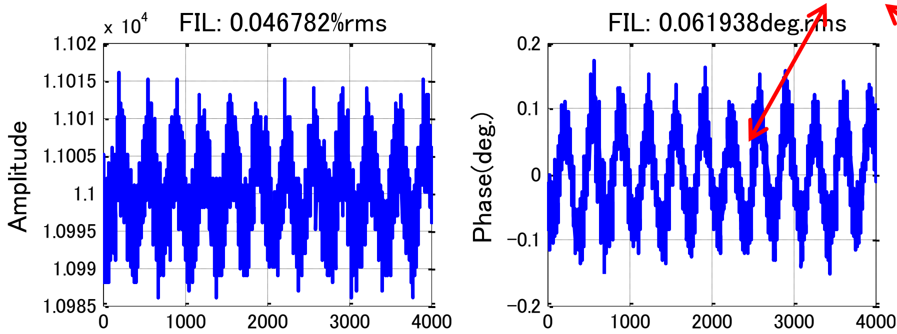
- The performance would be best in the optimal gain case.
- The amplitude and phase stability of Inj. 1 and Inj. 2&3 can be **0.01% RMS** and **0.02 deg. RMS**, respectively.

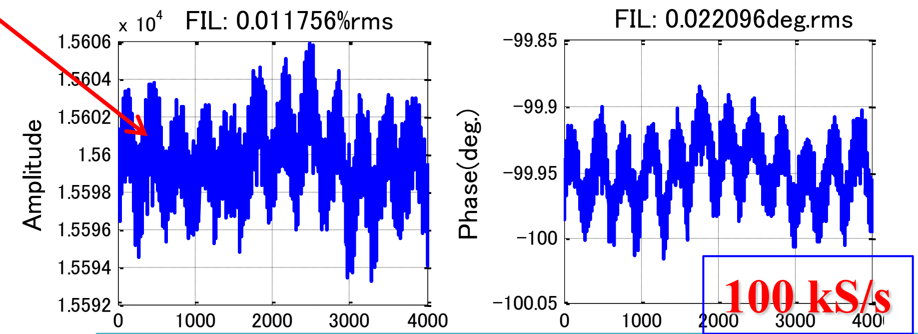
Performance (RF field)

FB0 (Buncher)

300 Hz fluc. from HV Power Supply

FB2 (Vector-sum of Inj. 2 and Inj. 3)





Amp 0.05% rms, Phase 0.06 deg. rms

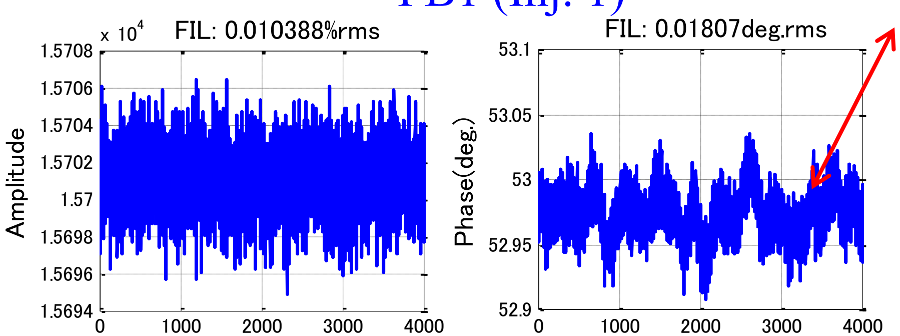
Amp: 0.01% rms, Phase 0.022 deg. rms

100 kS/s

Selections of KP and KI are based on the gain scanning experiment!

FB1 (Inj. 1)

No 300 Hz fluc.



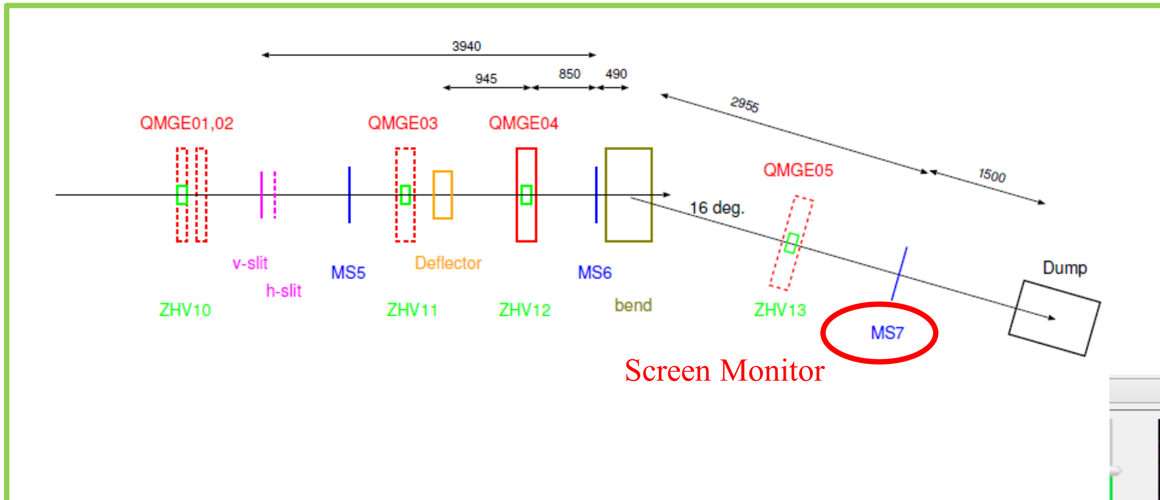
	ΔA/A [RMS]	*Δφ* [RMS]	*Loop Delay*
Bun.	0.05%	0.06 deg.	1.1 μs
Inj. 1	0.01%	0.02 deg.	1.1 μs
Inj. 2&3	0.01%	0.02 deg.	1.1 μs

Amp: 0.01% rms , Phase 0.02 deg. rms

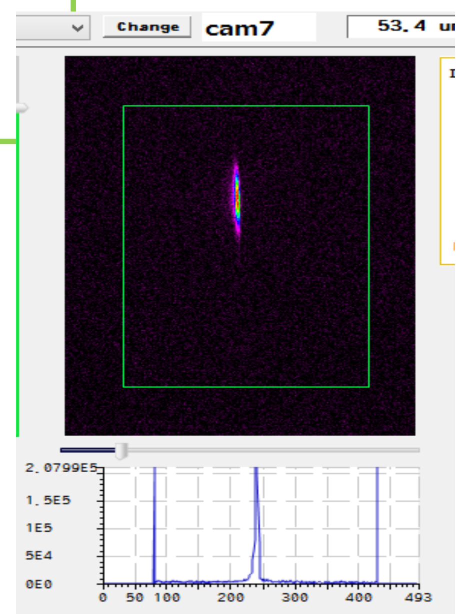
Our Goal:
0.1% for amplitude and 0.1 deg. for phase.

Performance (Screen Monitor)

- The beam momentum is measured by screen monitor and determined by the peak point of the projection of the screen.



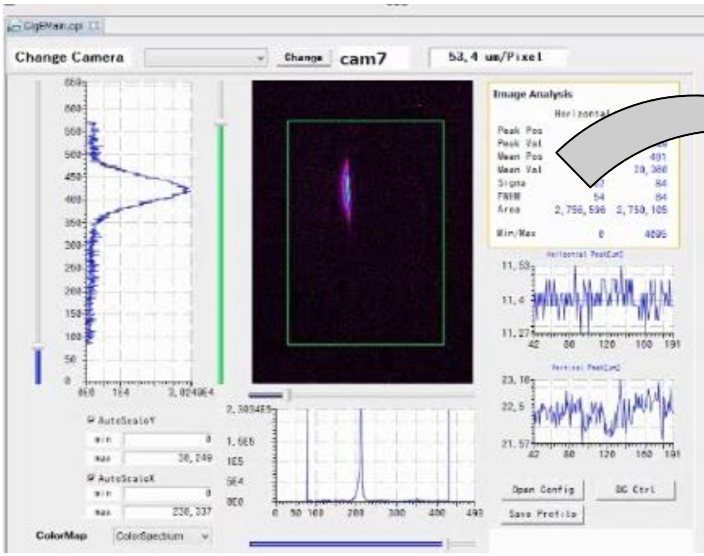
Dispersion @ screen monitor = 0.82m
Resolution = 53.4 μm/pixel
($\Delta P/P$=6.5e-5)



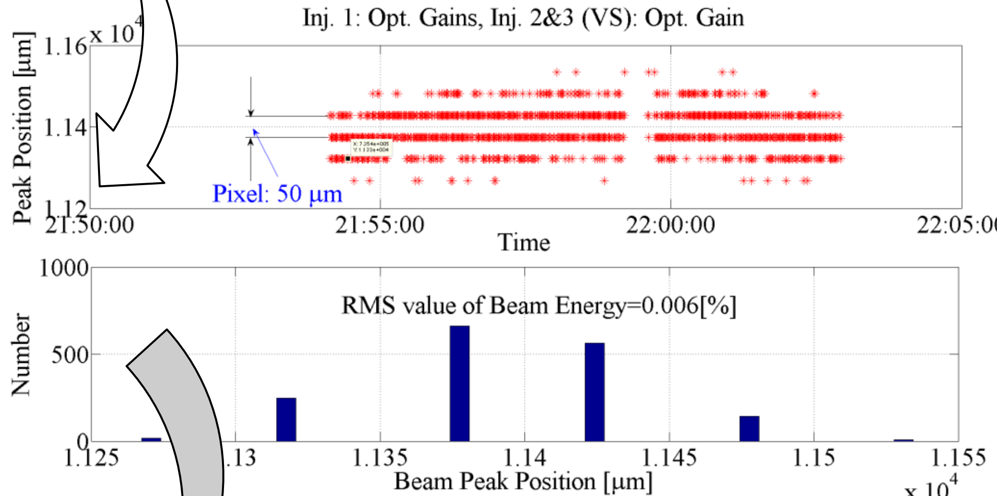
Momentum was determined by the peak point of the projection of the screen.

Attention: *Vector-sum error would influence the beam momentum jitter greatly! Thus the phase error btw inj. 2 and inj. 3 should be optimized at first!*

Performance (Beam energy)

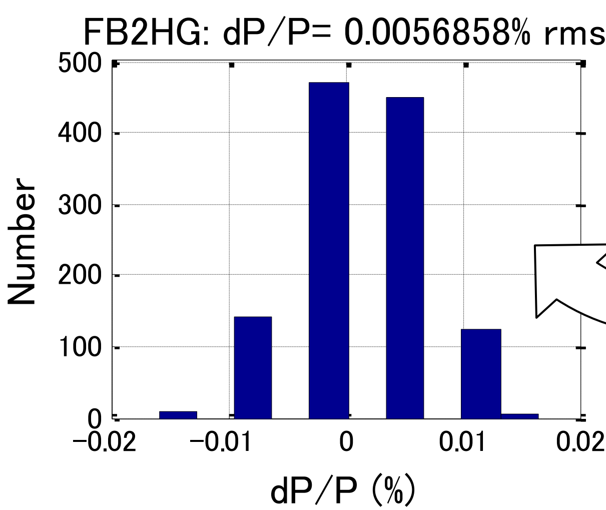


Result of the screen monitor



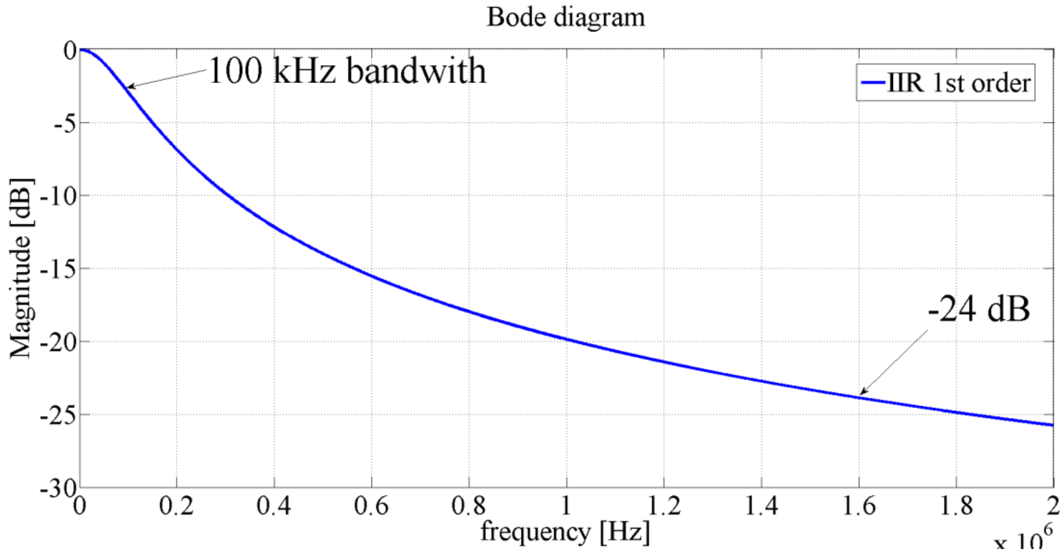
Momentum Jitter= 0.006% rms

Beam Energy



Future Plan

- Whole cERL operation would be carried out in October of 2013. At that moment, we will operate the main Linac 9-cell cavity.
- There are total 9 modes in the 9-cell cavity, only the π is selected as the accelerating mode .The $8/9\pi$ mode which is closed to π mode should be suppressed (otherwise, it would influence the system stability).
- The frequency of $8/9\pi$ mode of our cavity is about 1.6 MHz, we should remove it by digital filter, the current 1^{st} order IIR filter would only has about 24 dB suppression at 1.6 MHz with100 kHz bandwidth.



Obviously, the current 1^{st} IIR filter is not competent!
We should select other IIR filters.

$$Time: \quad y(n) = \alpha \cdot x(n) + (1-\alpha) \cdot y(n-1),$$

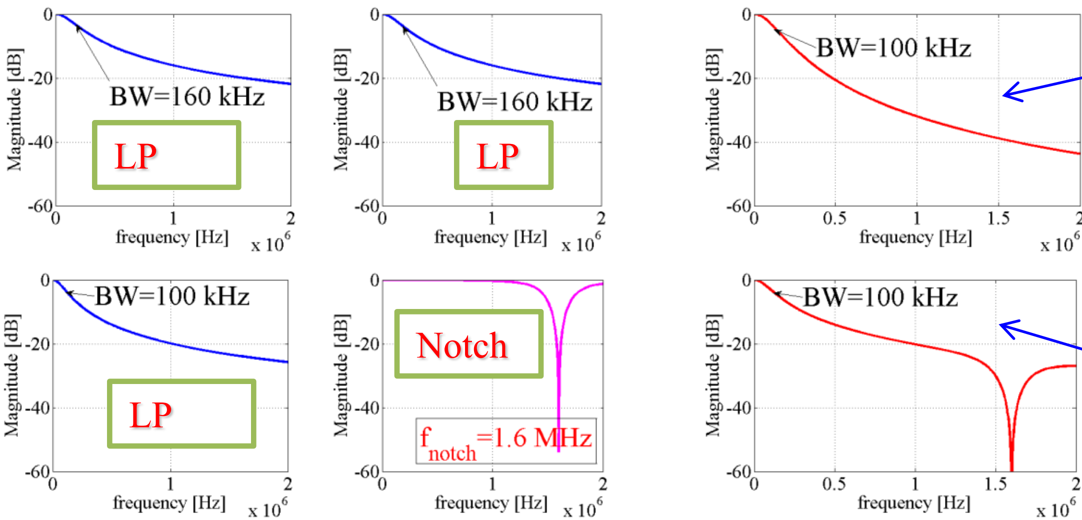
$$Frequency: \quad H(j\omega) = \frac{\alpha}{1-(1-\alpha)e^{-j\omega}}, \alpha << 1$$

Future Plan

■ Possible solutions:

a)Increasing the order of the filter (connecting the 1st order low pass IIR filter in series).

b)Application of the notch filter (band stop filter).

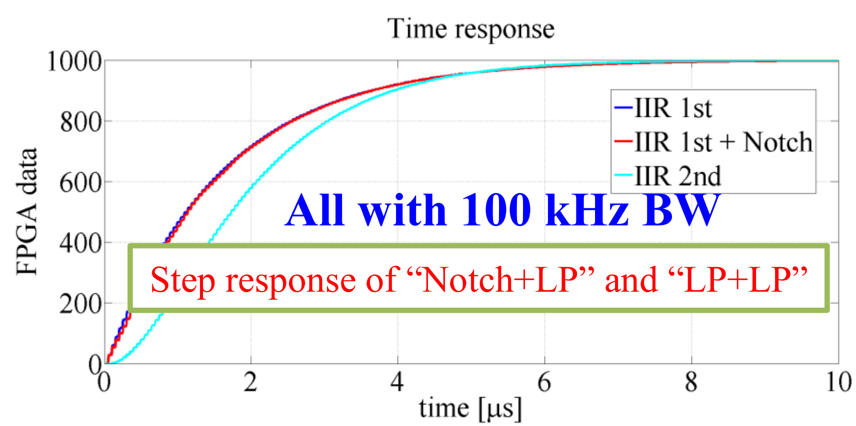


IIR LP +IIR LP

Which would be better!
We will compare.

IIR LP + Notch

Step response shows the Notch filter is attractive choice with same bandwidth (100 kHz)



Summary

Summary

- Construction of the RF system for cERL-injector was finished.
- Optimal gains has been determined in the operation.
- The power supply caused 300 Hz fluctuation is suppressed by high gain controlling.
- RF field requirements is satisfied.
- Very good beam momentum.

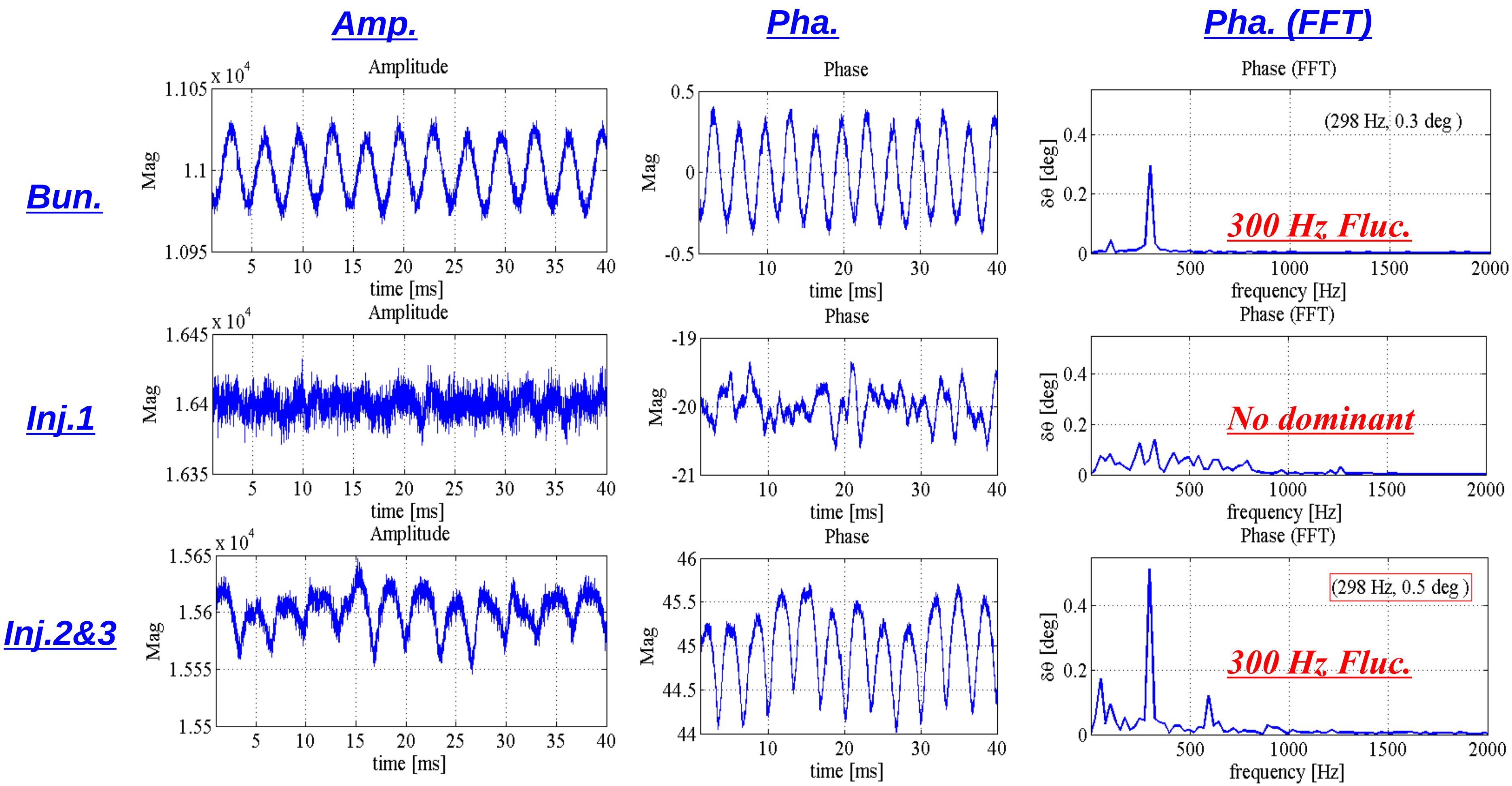
Question?

Thank you very much for your attending

Back up

Performance (300 Hz Fluctuation)

- The 300 Hz fluc. at Inj2&3 and Buncher cavity during CL/OL operation. This 300 Hz fluctuation would influence the system performance.
- The Inj. 1 LLRF system doesn't not has evident dominant components.

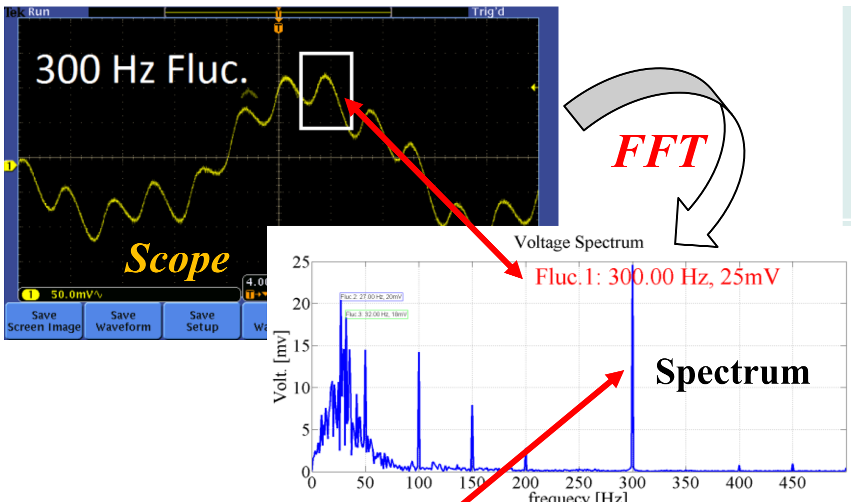


Study at cERL (2013)

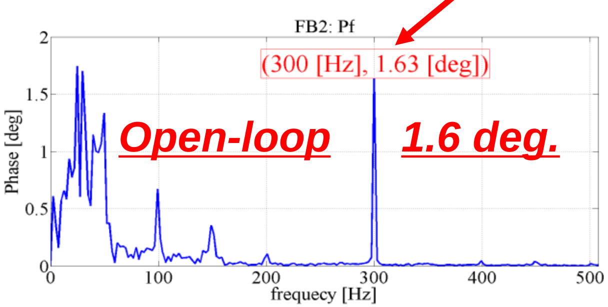
Performance(300 Hz fluc. suppression)

- The Power supply is the main source of the 300 Hz component.
- The RF fluctuation agrees well with the PS fluctuation (suppose 10 deg /HV%, then the 20mV fluctuation in PS will lead to 10 deg×(100×25mv/15V) = 1.67 deg).

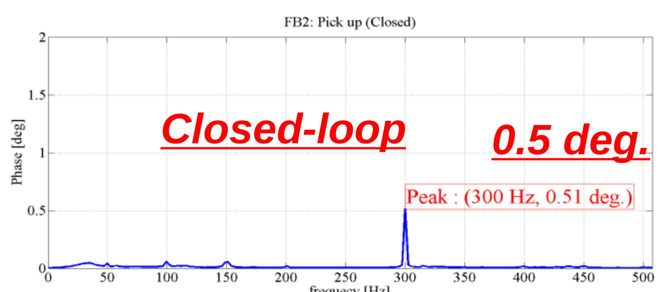
300 KW Kly. High Voltage



Fluc. @ 300 Hz		Buncher	Inj2&3 (VS)
Open loop	$\Delta A/A$	-43.5 [dB]	-46 [dB]
	$\Delta\theta$	0.9 [deg.]	1.6 [deg.]
Closed loop (*KI*=5500, *KP*=0)	$\Delta A/A$	-54 [dB]	-56.5 [dB]
	$\Delta\theta$	0.3 [deg.]	0.5 [deg.]



Cavity input (OL)



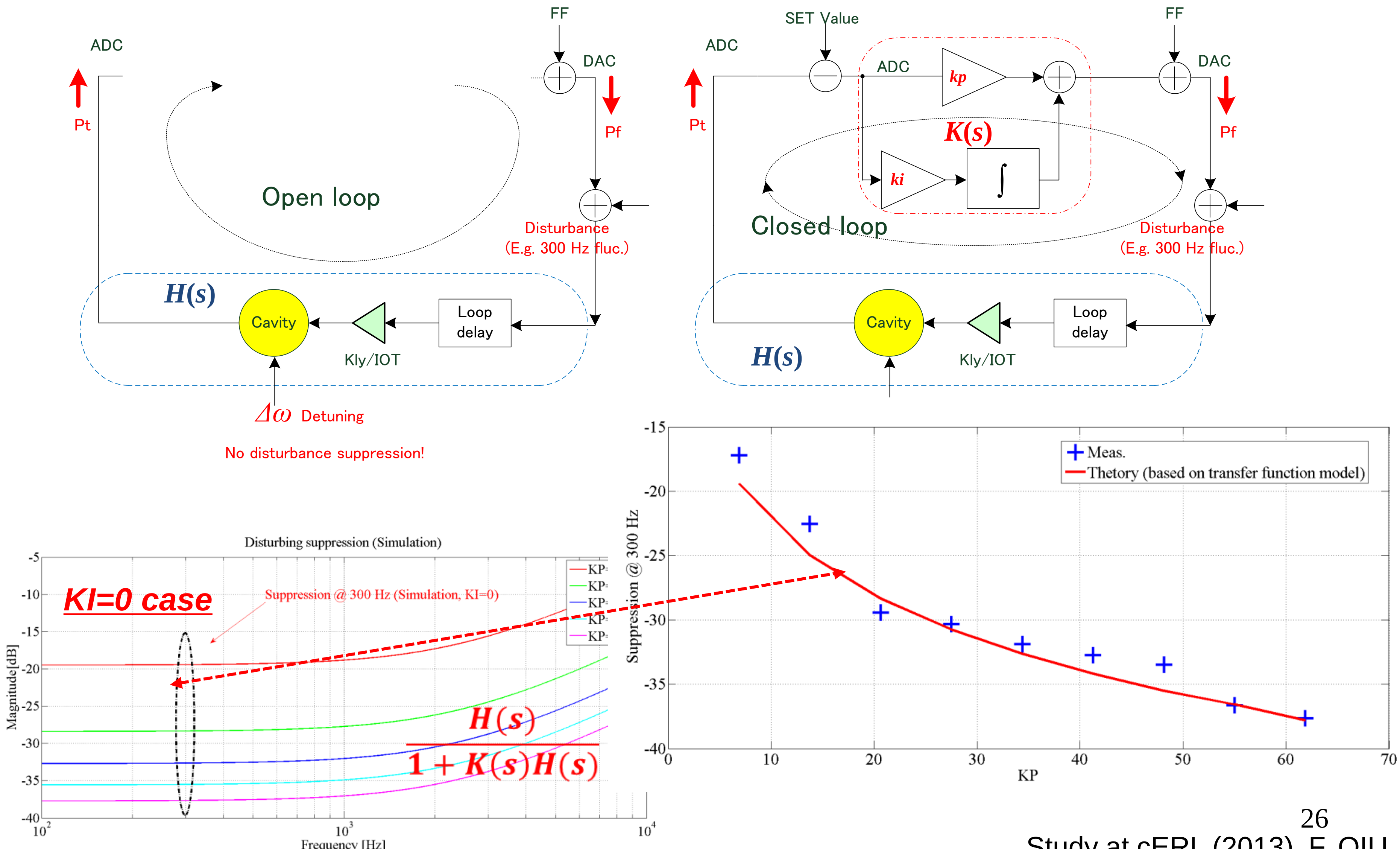
Cavity Pick up (CL)

Clear to see that the 300 Hz component is suppressed by CL operation.

Study at cERL (2013), F. QIU

Gain scanning (300 Hz suppression)

- The 300 Hz fluctuation would be suppressed by higher gains.

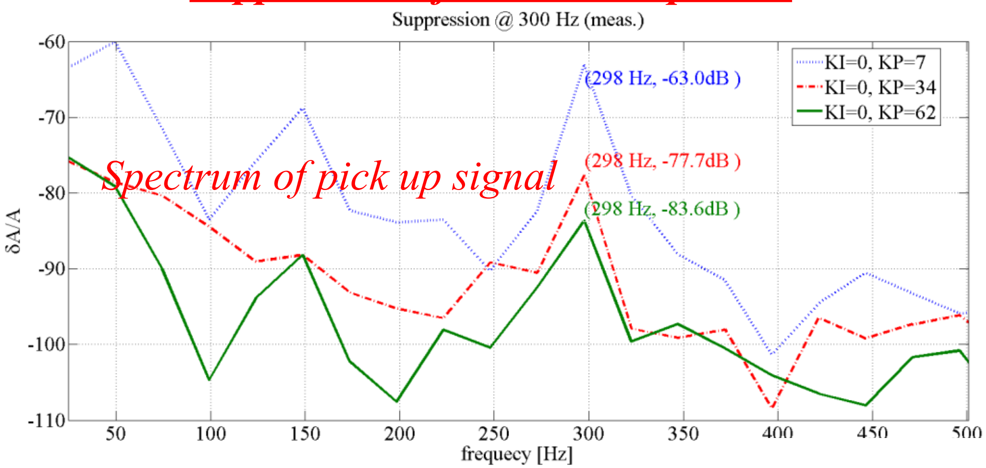


Study at cERL (2013), F. QIU

Performance(300 Hz fluc. suppression)

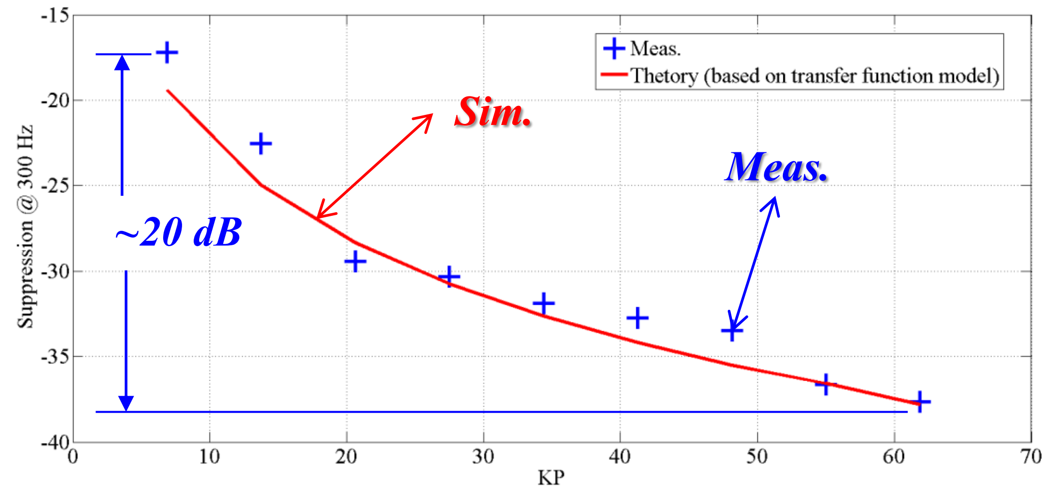
- The 300 Hz component is suppressed by high gains.

<u>Suppression of 300 Hz component</u>



About 20 dB suppression when increasing KP by 9 times.

<u>Meas. vs. Simulation</u>

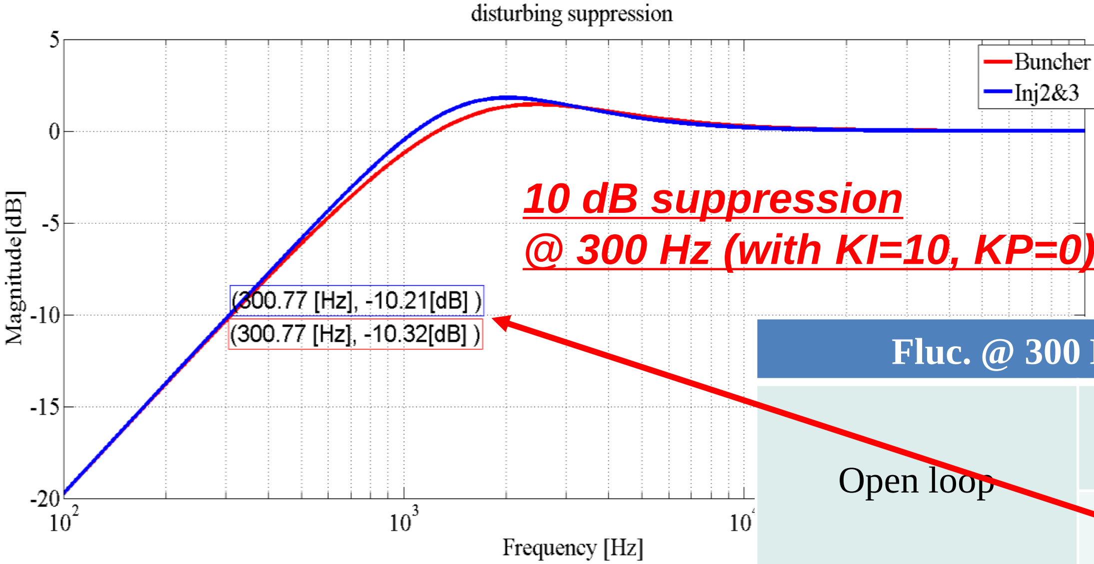


The simulation agrees well with the measured one

Study at cERL (2013), F. QIU

Fluctuation at 300 Hz (Source)

- According to current controlling parameter (KI=10, KP=0), the 300 Hz component is suppressed by ~10 dB (~3 times), not enough.



Fluc. @ 300 Hz		Buncher	Inj2&3 (VS)
Open loop	$\Delta A/A$	-43.5 [dB]	-46 [dB]
	$\Delta\theta$	0.9 [deg.]	1.6 [deg.]
Closed loop (KI=10, KP=0)	$\Delta A/A$	-54 [dB]	-56.5 [dB]
	$\Delta\theta$	0.3 [deg.]	0.5 [deg.]

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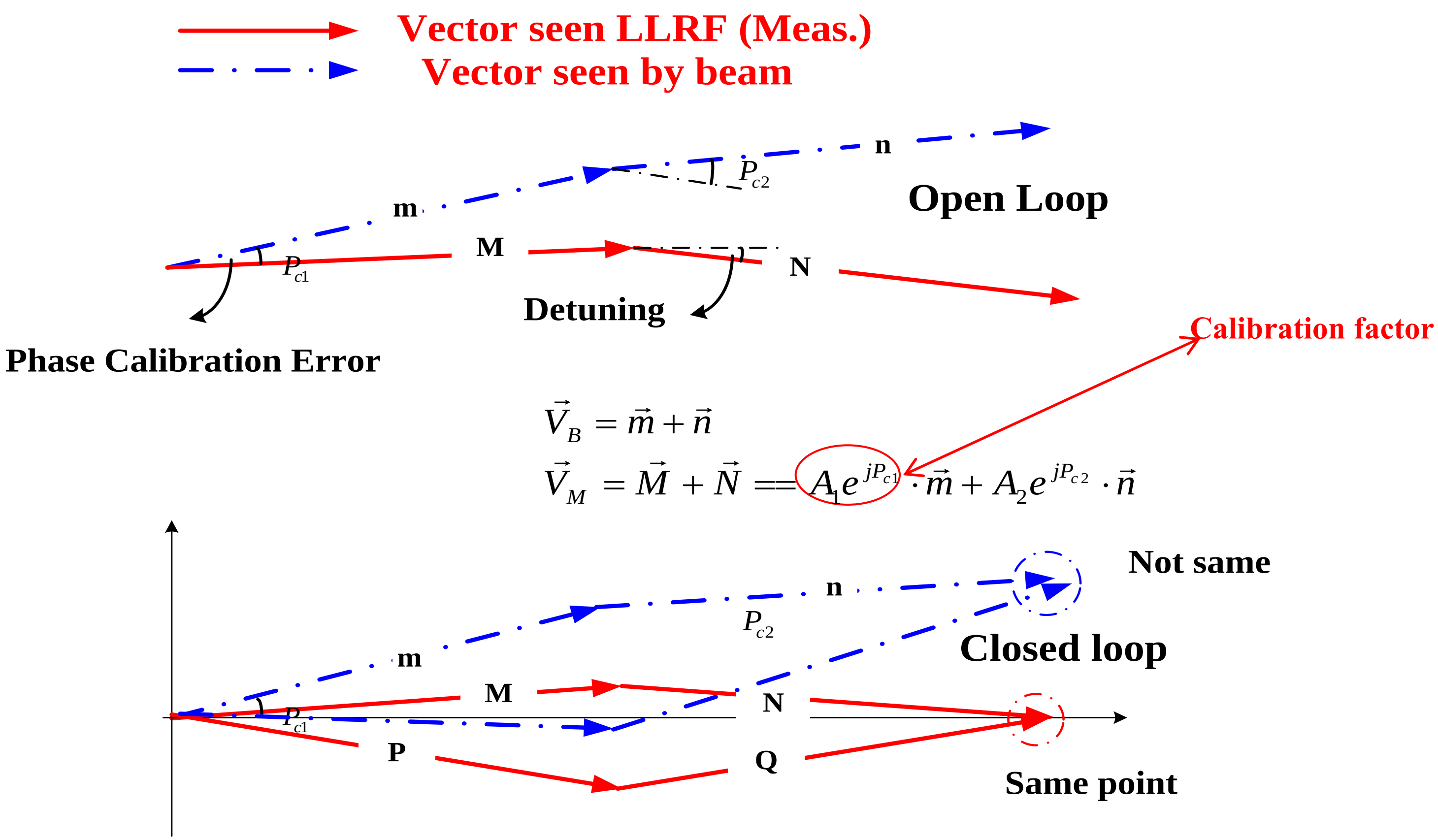
Performance (Vector-sum controlling)

- We have used the vector-sum controlling for Inj. 2 and Inj. 3 (see page 4&5 in this report).
- For vector-sum controlling, the measured vector-sum (***M***+***N***) which is seen by the FPGA or DSP is different from the true accelerating voltage which is seen by the beam (***m***+***n***).
- The calibration (phase or amplitude) error would result of vector-sum error



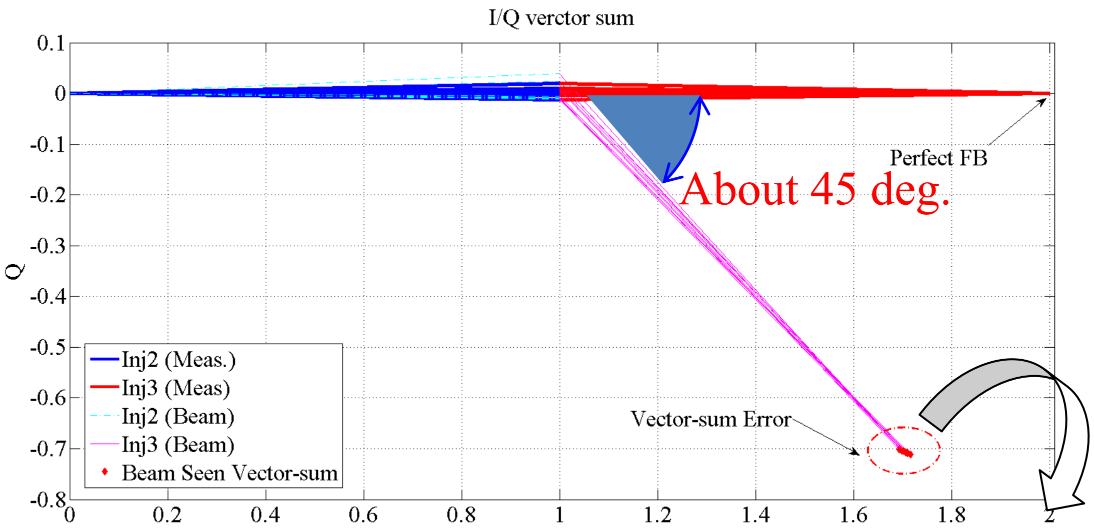
$$\vec{V}_B = \vec{m} + \vec{n}$$

$$\vec{V}_M = \vec{M} + \vec{N} == A_1 e^{jP_{c1}} \cdot \vec{m} + A_2 e^{jP_{c2}} \cdot \vec{n}$$

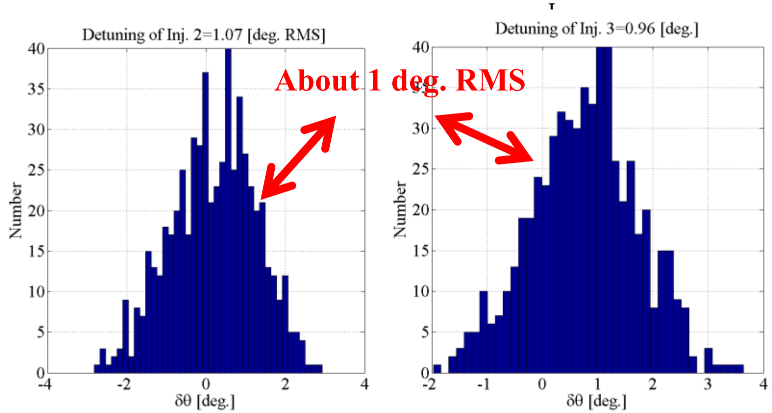
Study at cERL (2013), F. QIU

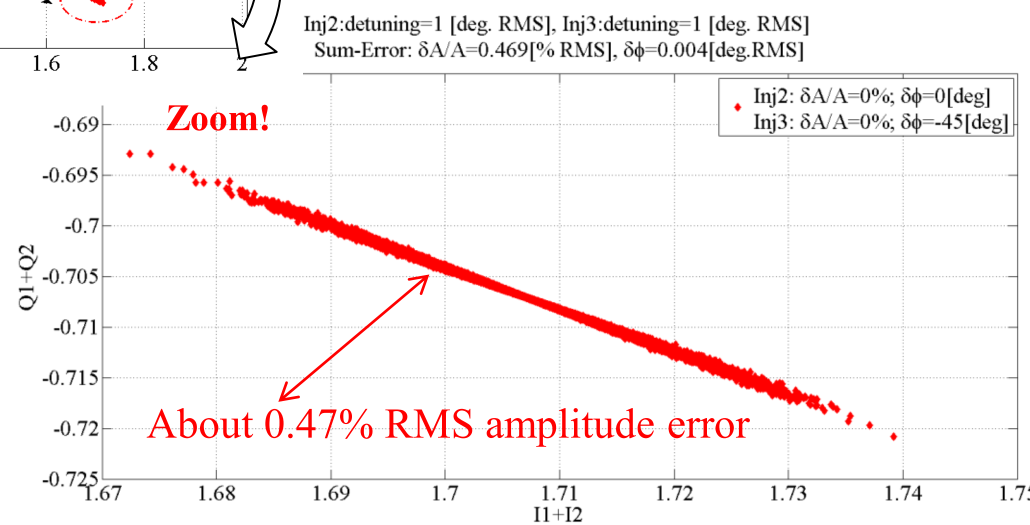
Performance (Vector-sum controlling)

- Suppose the detuning comply with 1 deg. RMS Gauss distribution, similar with the measured result, then the 45 deg. Phase calibration error would result of 0.47% RMS amplitude vector-sum error.



45 deg. calibration error would result of 0.47% RMS vector-sum error!





Distribution histogram of the detuning, similar with Gauss distribution.

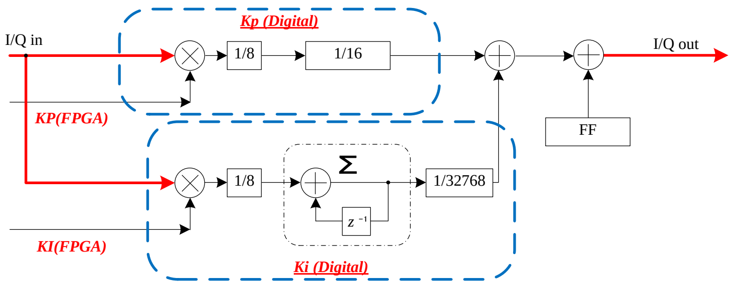
Study at cERL (2013), F. QIU

Gain scanning (definition)

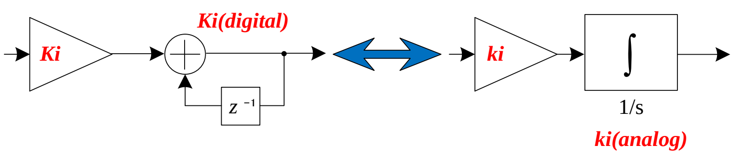
- Gain scanning: determine the optimal controlling gains (@ 2MV).
- Definition of the integral and proportional gains .

I. FPGA input parameter *KP* and *KI*.
II. Digital Gain *Kp* and *Ki*.
III. Analog Gain *kp* and *ki*.
IV. Real Gains: $A_{Set}/(A_{Set}-A_{Meas}.)$

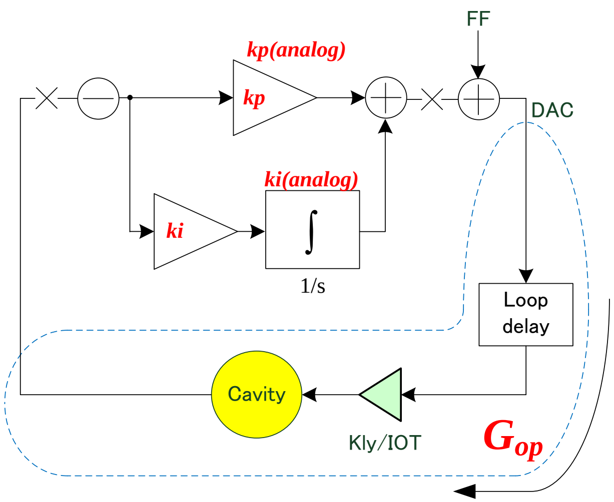
Gains	Integral	Proportional
FPGA	KI	KP
Dig.	$Ki=KI/2^{18}$	$Kp=KP/2^{7}$
Ana.	$ki=Ki/T_S^{(1)}$	$kp=Kp$
Real	$\approx ki*G_{op}^{(2)}$	$\approx kp*G_{op}$



KI&KP **(FPGA) vs.** ***Ki&Kp*** **(dig.)**



Ki **(dig.) vs.** ***ki*** **(ana.)**



ki&kp **(ana.) vs. real gain** $A_{Set}/(A_{Set}-A_{Meas}.)$

1 .T_S is FPGA sampling clock period (T_S= 1/162.5e6 in cERL LLRF system)
2. G_{op} is the open-loop gain (Gains from FF to SEL(Fil) during the open-loop operation. For the Inj1 and Inj2&3, $G_{op} \approx 1$ (0 dB).)